Supporting information

Geometrically-tunable beamed light emission from a quantum-dot ensemble near a gradient metasurface

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Electric-field-intensity distribution near the metasurfaces under external illumination

As described in the experimental section of the main text, the metasurfaces developed in this work are initially designed and optimized using a simulation method based on the principle of reciprocity. In these simulations, the metasurface is illuminated with an externally incident plane wave at the design wavelength of 800 nm and the average electric-field intensity on a plane at a near-field distance from the nanoparticles (NPs) is calculated as a function of angle of incidence. By reciprocity, the resulting trace is proportional to the radiation pattern of an ensemble of light-emitting electric dipoles located on the same monitor plane. Here we discuss the electric-field-intensity spatial distribution near the metasurface computed for a representative design (the structure with 750-nm array period) under illumination at its angle of peak response (θ_{cap} = 20°).

Figure S1(a) shows the field intensity (normalized to that of the incident plane wave) as a function of position along the x-direction (the in-plane direction perpendicular to the rectangular NPs),
within a unit cell on different monitor planes at different distances from the NPs. The field-intensity distribution on the x-z plane is displayed in the color map of Figure S1(b). Pronounced peaks of highly enhanced field intensity are observed at hot spots near the corners of the NPs, which rapidly decrease and broaden with increasing distance from the metasurface.

**Figure S1.** Calculated electric-field-intensity distribution near a representative metasurface (with 750-nm period), under x-polarized external plane-wave illumination at the angle of peak response ($\theta_{\text{cap}} = 20^\circ$). (a) Electric-field-intensity enhancement within a unit cell of the metasurface versus position along the x-direction, at four different near-field distances from the NPs. The positions and dimensions of the NPs are illustrated by the orange rectangles in the lower panel. The positions indicated by the red arrows are used in the 3D calculations of the full radiation pattern described in the main text. (b) Electric-field-intensity distribution in the x-z plane. The outlines of the Au NPs and SiO$_2$ spacer layer are indicated by the red and blue lines, respectively. The incident light wavelength is 800 nm.

To elucidate the nature of these hot spots, in **Figure S2(a)** we plot the field-intensity profile near the same metasurface (on the plane at 3 nm above the NPs) for different wavelengths of the incident plane wave, ranging from 740 nm to 860 nm. The field-intensity peak near each NP corner is found to exhibit a resonant dependence on wavelength, consistent with the behavior of localized plasmonic resonances of metallic NPs. The wavelength of maximum intensity is
different for different locations – for example, the hot spot at the left corner of the leftmost NP (75-nm-wide) is peaked near 780 nm, while the one at the right corner of the rightmost NP (150-nm-wide) is peaked at 840 nm. More in general, the detailed wavelength dependence of these resonances appear to be quite complex, likely as a result of near-field interactions between neighboring NPs and between the NPs and the underlying Au film. As shown in Figure 2(b), the spatially averaged field-intensity enhancement on the same monitor plane is peaked at 840 nm, where two particularly strong hot spots are obtained near the two rightmost NPs.

![Figure S2](image)

**Figure S2.** Calculated spectral dependence of the electric-field-intensity distribution near the same metasurface of Figure S1. (a) Electric-field-intensity enhancement within a unit cell of the metasurface versus position along the x-direction, at different illumination wavelengths between 740 and 860 nm. The monitor plane is 3 nm above the NPs. (b) Spatially averaged field-intensity enhancement on the same monitor plane versus wavelength.

The full radiation pattern produced by each device (as shown in Figure 3 of the main text) is computed by adding the results of multiple 3D simulations, where an electric dipole source is located at different positions of particularly strong local field intensity. For the representative design of Figure S1(a), these positions are indicated by the arrows in the second panel from the bottom of the figure. The choice of these locations is again dictated by the principle of reciprocity, whereby the emitters at these positions are expected to provide the strongest contribution to the
output light. At the same time, it is important to note from Figure S1(a) that a substantial field-intensity enhancement is obtained throughout the region where the light-emitting quantum dots (QDs) are distributed in the experimental devices, which extends across the entire sample area up to about 30 nm above the top of the NPs. Away from the hot spots, such enhancement originates from the surface plasmon polaritons supported by the underlying metal film, rather than from any localized NP mode (although significant mixing of propagating and localized plasmonic excitations can be expected). The implication is that all the QDs experience a strong interaction with the metasurface, leading to the observed directional modification of the radiation pattern for the entire QD ensemble.